LIQUID HANDLING USING EXPANDABLE MICROSPHERES

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ABSTRACT

In this study we introduce two novel concepts for fluid handling in microfluidic systems and show their realization in micromachined test structures: a one-shot micropump and a normally open one-shot valve. Both principles use Expancel® microspheres, which are small spherical plastic particles that, when heated, increase their volume by a factor of about 60. The expansion is irreversible, *i.e.* when cooled again, the expandable microspheres do not shrink.

INTRODUCTION

Miniaturization of fluidic systems in chemistry and biomedicine allows the reduction of the amount of chemicals, increases sensitivity and speed of an analysis, offers portability of the instrumentation or equipment and potentially reduces production costs through batch fabrication or high volume replication techniques. The handling of small amounts of liquids is therefore a growing field in microsystem technology (MST) and referred to as microfluidics.

Actuators displacing liquid volumes are essential components in fluidic chips and in some of the applications, a liquid volume is displaced only once, unidirectionally (*e.g.* injection of a drug *in vivo*). Conventional micropumps based on, for example, piezoelectric, electrostatic, or electromagnetical actuators require a relatively complex assembly which limits their use in disposable devices [1, 2, 3]. Direct electrical actuation of liquids can be subdivided into several pump principles: (i) Flow systems based on electroosmotic flow [4, 5, 6] or dielectrophoresis [7, 8] experience practical problems since the flow is strongly dependent on the composition of the flow medium. (ii) Electrohydrodynamic pumps can pump dielectric liquids but suffer from relatively complex electrical wiring [9]. (iii) Electrochemical pumps use electrolysis to produce a gas bubble which actuates the liquid [10]. Innovative approaches such as pumps and valves made in multi-layer soft lithography devices [11] or analytical systems using centripetal forces of rotating microfluidic systems made by compact disk (CD) replication technology [12] need relatively bulky external equipment to actuate the liquid.

In this work we suggest expandable microspheres, or beads, to be used in a novel concept for a one-shot unidirectional liquid actuator, *i.e.* a one-shot pump. Expandable microspheres (Expancel, Sundsvall, Sweden) are small spherical plastic particles. Their gas tight thermoplastic shell is enclosing a liquid hydrocarbon. When heated, the hydrocarbon undergoes a phase change to gas, the thermoplastic shell softens, and the volume of the microspheres increases considerably, much like the inflating of a balloon, as schematically shown in figure 1a). The dramatic volume increase is irreversible. The expandable microspheres are available with expansion temperatures in the range of 70 – 200 °C whereby the volume is increases with temperature. If the temperature increased above that at which the highest expansion is obtained the microspheres collapse [13]. Instantaneous heating results in instantaneous expansion (below 1s).

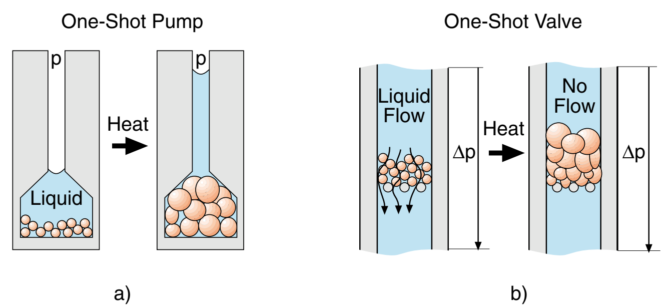

Figure 1: Two concepts for liquid handling by Expancel beads. a) a one-shot pump, b) a normally open one-shot valve.

In addition to fluid actuation, fluid control is of importance in a microfluidic system. It will almost inevitably involve valves, which may block the channels. A novel one-shot valve principle based on expandable microspheres is also introduced in the present work. The normal state is open, the actuated irreversible state is closed, as shown in figure 1b). One-shot valves have been shown before [14, 15] mainly for the controlled release of chemicals. However, their normal state is closed and their actuated state opened. Other microvalve principles based on polymer materials are, for example, functional hydrogel structures. These structures sense the pH of the surrounding environment and expand or contract accordingly [16, 17], thus no electrical stimulus is required for actuating of the valve.

The goal of this paper is to study the expansion of expandable microspheres in microfluidic channels and to demonstrate the feasibility of pumps and valves based on expandable microspheres.

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EXPERIMENTAL

The first liquid actuator and valve based on expancel microspheres are realized in micromachined test structures. For the sake of a general approach and similar experimental steps, both principles are tested in identical structures.

The test structures consist of silicon microchannels, in the following referred to as inlet and outlet, as shown in figure 2, covered by a glass lid. The width of the inlet channel is typically 100 or 200 µm, the width of the outlet 20 or 50 µm. The depth of both channels is 50 µm. The channels are manufactured using silicon deep reactive ion etch (DRIE) technology. The micromachining process is described below. A prerequisite for using expandable microspheres in fluid handling is the ability to selectively place them in a predefined area of the microfluidic system. It was decided to localize the expandable microspheres via microfluidics on chip level, in contrast to our work presented in [17], where we have localized expandable beads via photolithography or surface chemistry on wafer level. Upon applying a 2 µl mix of expandable microspheres (Expancel 820 DU) and de-ionized (DI) water to the inlet, the mix is sucked into the chip by capillary forces, as depicted in figure 3a). A filter consisting of high aspect ratio pillars prevents the passage of microspheres into the outlet channel. The beads are between 5 and 20 µm in diameter. A flow of DI water is generated by applying pressure at the inlet channel, thus packing the microspheres at the filter location, as shown in the drawing of figure 3b). The size of the bead pack was controlled via the concentration of beads in the mix.

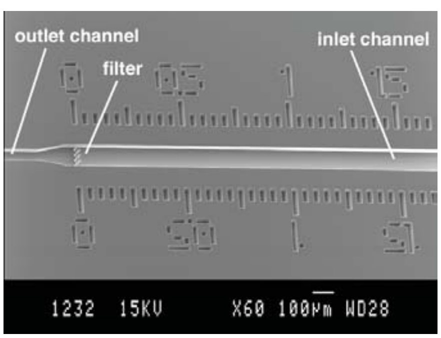


Figure 2: Deep reactive ion etched test channels. The smallest tick of the ruler corresponds to 50 µm.

The principle for a one shot pump is shown in figure 1a). As it can be clearly seen, the structure is a container having only one opening. This configuration was achieved in the test structure by sealing the outlet microchannel using UV curing epoxy (Epotek OG 198), as depicted in figure 3c).

The outlet channel must not be sealed when demonstrating the valve principle.

We consider the pump principle as validated when it can be shown that expancel microspheres increase their volume against a pressure applied at the inlet. The increase in volume of the expandable microspheres is displaces the DI water in the channel by the same amount. A ruler is etched into the silicon beside the inlet, the “0-tick” starting at the filter. This on-chip measurement is used to measure the volume variation of the microsphere pack.

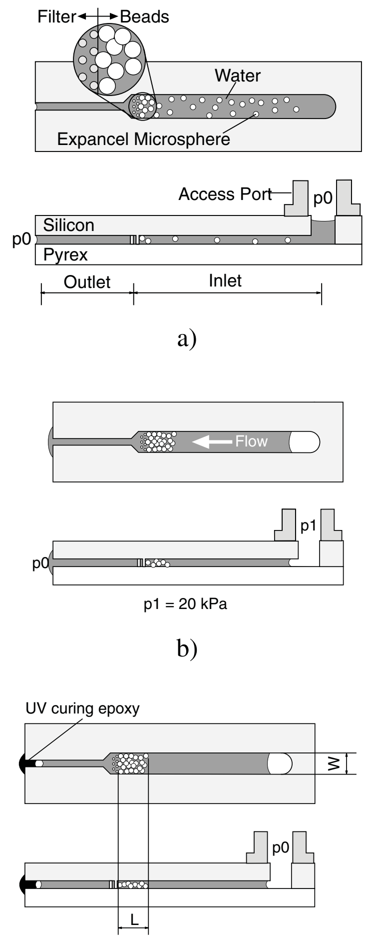


Figure 3: Schematic drawing of the microfluidic test structure filling with de-ionized water mixed with Expancel microspheres. a) the water-bead mix fills the channels by capillary forces. b) by applying a flow a bead pack is formed and water exits through the outlet channel. c) sealing of the outlet channel with UV curing epoxy. Step c) is omitted for valve tests.

We consider the valve principle as validated when it can be shown that unexpanded microsphere packs allow liquid flow and expanded beads block the liquid flow. To have an accurate measurement of the flow, a time of flight measurement of air bubbles intentionally introduced to the outlet or of particles (*e.g.* beads) introduced to the inlet is conducted.

All manipulations are done with the chip placed onto an aluminum chip holder allowing a precise temperature control of the chip. A silicone tube is connected to the access port providing desired inlet pressure, as shown in figure 4. The temperature of the chip holder is ramped up from room temperature to

70 °C in 3 min via a 3 W CMOS transistor. A temperature sensor placed on the aluminium holder allows closed loop temperature control. The heating is always stopped at 70 °C. Although the used beads would support higher temperatures without collapsing (*i.e.* approximately 120 °C), the temperature was not increased above 70 °C since excessive liquid evaporation or even bubble formation should be avoided. In this study, no work was done to control the size of the microspheres via temperature.

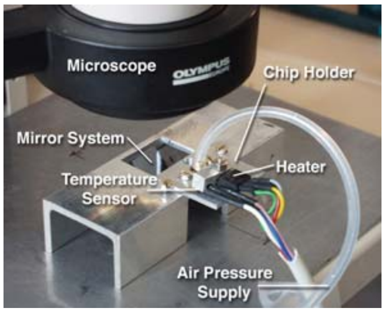
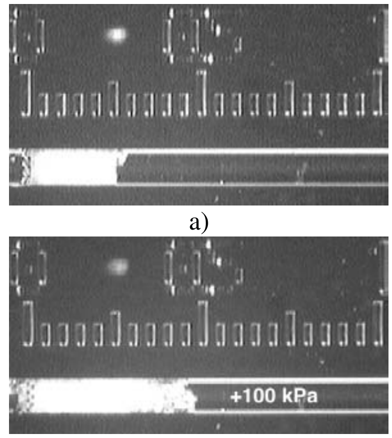


Figure 4: Photograph of the measurement set-up. A 3W CMOS transistor (= heater) and a temperature sensor are attached to an aluminium chip holder, thus enabling an accurate control of the chip temperature up to 80 °C. The mirror system facilitates channel observation during experiments. During heating the chip holder is placed on rubber pads to decrease heat loss.

All microfabrication steps use standard technology and processes. The microchannels along with the ruler are deep reactive ion etched (DRIE) in silicon using a silicon dioxide (SiO_2) mask, as depicted in figure 2. The wafer through liquid access holes are aligned and patterned into SiO_2 on the back side of the wafer. The wafer is subsequently glued on a dummy wafer using photoresist (the microchannels facing the resist) and the access holes are etched using DRIE. After releasing the device wafer from the dummy wafer, a Pyrex glass wafer is anodically bonded to seal the channels. A metallic access port is glued onto the chip at the location of the access hole to allow the coupling of a silicone rubber tube to the chip, see figure 3 and figure 4.

RESULTS AND DISCUSSION

The expansion of Expancel® microspheres heated from 23 °C (*i.e.* the measured room temperature) to 70 °C under applied counter pressure of 100 kPa is shown in figure 5. After the beads were cooled down to room temperature again, the pressure was varied between 20 kPa and 100 kPa whereby no volume variation of the microspheres was observed. This indicates that the microspheres expand regardless of a counter pressure of 100 kPa. It also means that once the liquid is displaced, it will not be possible for the liquid to flow back into the location where it was stored before the actuation, regardless of 100 kPa counter pressure and cooling of the microspheres. The somewhat arbitrary value of 100 kPa is imposed by the performance of the used current to pressure converter set up.



a)

b)

Figure 5: Microscope photographs showing a bead pack before (a) and after (b) a 70 °C heat treatment at 100 kPa counter pressure. The total expansion is 1.4 nl, the relative expansion approximately 200 %. At the filter, microspheres manage to squeeze somewhat in between the filter pillars.

The total volume of actuated liquid depends on the number of heated microspheres. A single bead can increase its volume by a factor 60 when heated to the maximal temperature before collapsing. Since the beads were only heated to 70 °C, we observed that the relative volume expansion of beads packed in a microchannel is significantly less. The measured expansion factors were below 5. Further, the expansion is dependent on the geometry of the bead pack. A bead pack can be characterized by the ratio of its length L and the width of the inlet channel W, as shown in figure 3c). The dependency of the relative volume expansion on the pack ratio L/W is shown in the graph of figure 6. A distinct trend indicates that to use expandable microspheres at their full potential, the L/W ratio of bead packs should be as small as possible.

The maximum measured volume expansion was 8 nl (i.e. $V_{initial}$ = 4 nl and $V_{expanded}$ = 12nl) and the minimum volume expansion was 1 nl (i.e. $V_{initial}$ = 1 nl and $V_{expanded}$ = 2nl). In the present study, the only way of controlling the pumped liquid volume is to control the number of packed beads because of the somewhat "digital" heating process (*i.e.* the temperature of the bead packs was always increased from room temperature to 70 °C). More work can be done in the future to investigate to cease the expansion (*i.e.* heating) when a desired amount of liquid is actuated.

In the one-shot valve experiments, a pressure of 20kPa was applied to a pack of unexpanded beads as shown in figure 7. The dimensions of the unexpanded bead pack are 100 x 600 x 50 μm^3. A water flow of approximately 0.8 µl/min resulted. Without the beads, a pressure of approximately 0.3 kPa is required to generate the same flow. The main pressure drop is thus created in the bead pack. After expansion, the expanded beads completely block the microchannel and impede any water flow up to a pressure of 100 kPa and the valve is closed, as depicted in figure 7.

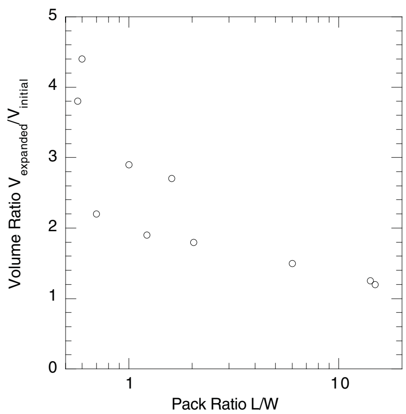
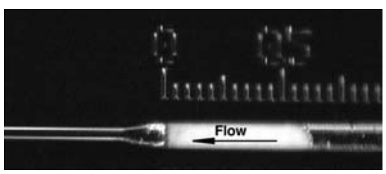
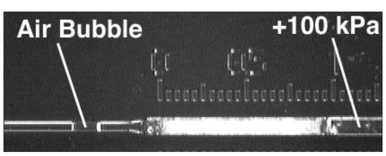


Figure 6: Relative expansion of bead packs after heating vs. the pack ratio of the unexpanded beads. The large spread of the measurements at a low pack ratio is due to the fact that the absolute expansion in this case is small which considerably increases the measurement error.



a)



b)

Figure 7: a) Water flow through unexpanded bead pack in the open valve situation. Expanded beads at b) +100 kPa of inlet pressure in the closed valve situation. The intentionally introduced bubble in the outlet channel does not move or change size, regardless of whether pressure is applied or not. Thus, the channel is blocked.

CONCLUSION

We have demonstrated that expandable microspheres are suited for liquid handling in microfluidic chips. Water in the nanoliter range was displaced in a microchannel against a counter pressure of 100 kPa (*i.e.* the microspheres act as a one-shot pump). The flow of water in a microchannel was completely blocked (*i.e.* the microspheres act as a one-shot normally open valve).

The main factors influencing the effectiveness of the liquid actuation are heating temperature and geometry of the packed expandable microspheres.

The presented liquid handling principles are largely independent of the liquid properties and offer a very high energy density. The presented pump principle has high potential for active liquid dosing, in drug delivery, for example. An interesting feature is that the liquid cannot flow back into the container once it is actuated.

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